A FULL WAVE STUDY OF RADAR CROSS SECTIONS
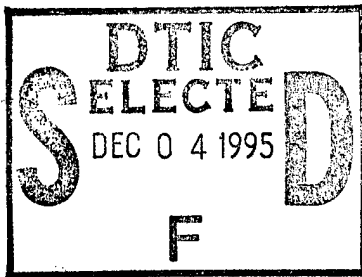
OF ROUGH TERRAIN

Final Report

Ezekiel Bahar

Principal Investigator

August 31, 1994

University of Nebraska-Lincoln

and

Center for Electro-Optics

19951129 111

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE December 31, 1994	3. REPORT TYPE AND DATES COVERED Final 6/24/91 to 12/31/94

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
A Full Wave Study of Radar Cross Sections of Rough Terrain	

6. AUTHOR(S)

Dr. Ezekiel Bahar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Nebraska-Lincoln Electrical Engineering Department & Center for Electro-Optics 209N WSEC Lincoln, NE 68588-0511	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211	

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

Full wave solutions are derived for the like and cross polarized electromagnetic diffuse single scattered fields from two dimensional irregular stratified media. Scattering upon reflection and transmission across random rough surfaces is considered. The surface is characterized by its joint probability density function for the heights and slopes at two points. The full wave expressions involve the height/slope correlations. The full wave results are compared with the small perturbation physical/geometrical, numerical (based on Monte Carlo simulations) and experimental results.

Full wave solutions for the double scatter fields and cross sections are also derived for rough surfaces that exhibit enhanced backscatter. The solutions are expressed as an interaction integral between two single scatter cross sections associated with quasi parallel and quasi antiparallel paths. The dependence of the angular width and level of the enhanced backscatter cross section on the mean square height and slope and on the mean width of a typical depression on the rough surface is determined. The results are compared with numerical and experimental data.

14. SUBJECT TERMS		15. NUMBER OF PAGES
Single and Double Radar Cross Sections, Enhanced Backscatter, Random Rough Surfaces		
		16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Table of Contents

I. INTRODUCTION

Traditionally, physical optics and perturbation theories have been used to derive the like and cross polarized scattering cross sections for composite random rough surfaces. To this end two-scale models have been adopted and the rough surfaces are regarded as small scale surface perturbations that are superimposed on large scale, filtered surfaces. Using this model the scattering cross sections are expressed as sums of two cross sections. In general, however, the restrictions on both the large and small scale surfaces cannot be satisfied simultaneously using the perturbed-physical optics approaches. Furthermore the results based on the two-scale model, depend on the wavenumber where spectral splitting is assumed to occur between the large and small scale surfaces. The perturbed physical optics approach (based on a two scale model) cannot be used to correctly predict the backscatter cross polarized cross sections since the cross polarized contribution from the large scale surface is assumed to be zero. Thus, the two-scale model cannot be effectively applied to polarimetric radar studies.

More recently, the full wave solution, based on a rigorous mathematical approach, has been used to determine the scattering cross sections for composite random rough surfaces of finite conductivity. Through the use of rough surface height conditional joint characteristic functions (that account for the rough surface height/slope correlation); it is shown that the same full wave solutions for the diffuse scattered fields are in good agreement with the perturbation solutions when the rms height and slopes are of the same order of smallness and with the physical/geometrical optics solutions at high frequencies. The full wave solutions account for Bragg scattering and specular point scattering in a unified self-consistent manner. Using the unified full wave approach, it is possible to analyze more realistic models of propagation paths over rough terrain.

The full wave approach can be used to evaluate the bistatic scattering cross sections for all incident and scattered wave directions. These results have been validated by comparisons with insitu measurements and laboratory experiments and numerical solutions based on Monte Carlo simulations (Bahar and Lee 1994). Data on scattering from rough surfaces indicate that the full wave approach correctly predicts the like to cross polarized scattering cross section ratio for rough seas (Daley et al 1970, Bahar and Fitzwater 1985). Furthermore, the full wave approach correctly predicts backscatter enhancement observed in controlled laboratory experiments using fabricated surfaces with different roughness scales (Bahar and El-Shenawee 1994). It has also been used to correctly interpret the Lunar surface data (Bahar and Haugland 1994).

In the work based on the full wave approach, the medium below the rough interface is characterized by a complex permittivity to account for its finite conductivity. This has an important impact upon both single scattering and multiple (double) scattering by rough surfaces. The results for the radar cross sections are consistent with measurements conducted in a controlled laboratory environment. The full wave approach has also been applied to rough surfaces with non Gaussian surface height probability density functions as well as to irregular stratified media. Thus reflection and transmission across thin films with rough interfaces can be investigated. The full wave results are fully polarimetric. These polarimetric full wave investigations will enhance the potential for remote sensing since they include magnitude and relative phase data contained in the sixteen Mueller (Stokes) matrix elements.

II. MOTIVATION AND RESEARCH OBJECTIVES

Physical optics and perturbation theories have been used to derive the like and cross polarized scattering cross sections for composite random rough surfaces (Beckmann

and Spizzichino, 1963; Beckman, 1968; Rice, 1951). To this end two-scale models have been adopted and the rough surfaces are regarded as small scale surface perturbations that are superimposed on large scale. filtered surfaces (Wright, 1968; Valenzuela, 1968; Barrick and Peake, 1968).

Thus the scattering cross sections are expressed as sums of two cross sections. The first accounts for specular point scattering. It is given by the physical optics cross section for the filtered surface consisting of the large scale spectral components. The second accounts for Bragg scattering. It is given by the cross section for the surface consisting of the small scale spectral components that ride on the filtered large scale surface.

On applying the perturbed-physical optics approaches it is necessary to specify the wavenumber k_d where spectral splitting is assumed to occur between the large and small scale spectral components of the rough surface. In general the restrictions on both the large and small scale surfaces cannot be satisfied simultaneously and using the perturbed-physical optics approaches the evaluation of the scattering cross sections critically depends on the specification of k_d (Brown, 1978).

More recently the full wave solution based on a rigorous mathematical approach has been used to determine the scattering cross sections for composite random rough surfaces of finite conductivity (Bahar, 1981b; Bahar and Barrick. 1983). The full wave solutions account for Bragg scattering and for specular point scattering in a unified self-consistent manner. However. when such a decomposition is implemented, the full wave solutions for the scattering cross sections are expressed in terms of a weighted sum of two cross sections (Bahar, 1981b; Bahar and Barrick, 1983). Furthermore, in an attempt to draw more definite conclusions regarding the choice of k_d, it was varied over a wide range of values (Bahar et al., 1983a). It was shown that while, as expected, the like polarized cross sections associated with the

large and the small scale surfaces critically depend upon the choice of k_d, the full wave weighted sums of the like polarized cross sections remain relatively insensitive to variations in k_d . The physical optics approximation for the cross polarized backscatter cross section is zero. As a result, the cross polarized backscatter cross section for the large-scale surface is set equal to zero when the two-scale model is used. However. for backscatter, only the specular points on the rough surface do not depolarize the incident wave.

It is shown that while the full wave solutions for the like polarized scattering cross sections based on the two-scale model are in reasonable agreement (within 3 db) with the unified full wave solutions. the two solutions for the cross polarized cross sections differ very significantly for near normal incidence (about 15 db).

In a recent paper (Bahar, 1991) the full wave analysis has been provided for rough surface diffuse. incoherent radar cross sections with height-slope correlation included. Since the full wave rough surface element scattering coefficients are slope dependent. the expressions for the scattering cross sections involve the conditional joint characteristic functions for the rough surface height. It is shown (Bahar 1991) that when the root mean square height is small compared to wavelength and the slope is of the same order of smallness. the full wave solutions reduce to Rice's (1951) small perturbation solution. However, the same full wave expression for the incoherent scatter cross sections reduces to the physical/geometrical optics solution in the high frequency limit (Beckmann and Spizzichino, 1963). This is because, in the high frequency limit. the Foureir transform of the conditional joint characteristic function is proportional to the Dirac delta functions for the slopes at the stationary phase (specular) points on the surface.

Using the unified full wave approach it is, therefore, possible to analyze more realistic models of propagation paths. It is not necessary to resort to the artificial decomposition of the irregular terrain into large and small scale surfaces.

The full wave approach can be used to evaluate the bistatic scattering cross sections for all incident and scattered wave directions. These results have been validated by comparisons with insitu measurements and laboratory experiments. Work on scattering from rough surfaces indicates that the full wave approach correctly predicts the like to cross polarized scattering cross section ratio for rough seas (Daley et al., 1970, Bahar and Fitzwater, 1985). Furthermore, the full wave approach correctly predicts backscatter enhancement observed in controlled experiments using fabricated surfaces with different roughness scales (Bahar and El-Shenawee, 1991a, 1991b, 1994).

In this work the medium below the rough interface is characterized by a complex permittivity that accounts for its finite conductivity. This has an important impact upon both single scattering and multiple scattering by rough surfaces. Work on the computation of the full wave single and double scatter fields for deterministic and random rough surfaces has been conducted (Bahar and El-Shenawee, 1991a, 1991b, 1993). In this work the like polarized field scattered in the plane of incidence is evaluated for both vertically and horizontally polarized excitations. The effects of varying the following parameters are investigated: angle of incidence, mean square slope, mean square height, correlation length and complex permittivity of the scattering medium. The full wave results for the enhanced backscatter cross sections (due to double scatter) are shown to be in good agreement with experimental results (Knots et al. 1993, Bahar and El-Shenawee 1994). It is proposed to expand the investigation of multiple scattering from two dimensionally rough surfaces. Thus, both the like and cross polarized scattered field will be considered.

In order to determine the expected values of the scattering cross sections for random two dimensional rough surfaces, it is necessary to characterize the surface by conditional joint probability density functions for the surface heights and slopes at

8

two separate points. Such a probability density function accounts for the correlation between the slopes and heights. However, in order to simplify the analysis. the correlation between the surface heights and slopes are usually ignored. Using the full wave approach. the correlation between heights and slopes at two distinct points on the rough surface are accounted for (Bahar, 1991, Bahar and Lee, 1994). Both one dimensional and two dimensional rough surfaces (characterized by their surface height conditional joint probability density functions) are considered. This work sheds light on the source of the discrepancies between the physical optics results and the small perturbation results. Both like and cross polarized bistatic scatter cross sections are considered.

The first and second order small perturbation solution (Rice 1951) as well as the physical/geometric optics solution (Beckmann 1968, Brown 1978) for the cross polarized radar cross sections in the plane of incidence (including backscatter) are zero. However. for two dimensional rough surfaces the cross polarized cross section is not zero, since the normal to the surface is not in the plane of incidence. The hybrid solution based on the two scale model does account for depolarization in the plane of incidence (including backscatter) due to the small scale surface that rides on the large scale surface (Valenzuela 1968, Brown 1978). However, using the full wave approach. it is shown that both the large scale and small scale two dimensional surfaces depolarize the incident waves (Bahar and Fitzwater 1984). This is consistent with observations even when the slopes are not very large and multiple scatter is not significant (Daley et. al. 1970). Since cross polarization is included in the evaluation of the Mueller matrix elements for backscatter, this could have a significant impact on remote sensing applications.

For the small perturbation solution (Rice 1951) and for the physical optics solution, based on the Kirchhoff approximations for the surface fields (Backmann and

9

Spizziahino 1963) the surface element scattering coefficients are independent of slope while for the full wave solutions, which are invariant to coordinate transformations, the surface element scattering coefficients are slope dependent. For this reason the full wave solutions involve conditional joint characteristic functions for the surface heights, rather than the slope independent joint characteristic function (Bahar 1991). It is this unique feature of the full wave solution that permits the use of the same expression to account for Bragg scatter from the small scale spectral content of the rough surfaces as well as to account for the specular contributions from the neighborhoods of the stationary phase points on the rough surface.

In a recent work (Bahar and Lee 1994), a very comprehensive comparison has been conducted between the full wave results and the corresponding low frequency perturbation results and the high frequency physical/geometrical optics results as well as to experimental data and numerical data based on Monte Carlo simulations of rough surfaces. It is shown that when the rms height and slope are of the same order of smallness, the full wave results are in excellent agreement with the small perturbation results while at high frequencies they are in very good agreement with the physical/geometrical optics results. There is also good agreement with the experimental and numerical results for both polarizations. This work has also been extended to scattering upon transmission across rough surfaces.

Another important phase of these investigations is related to the effects of shadowing (Bahar, 1991). For example, a point on the surface is on the shadow boundary when the scalar product of the vector normal to the surface $\bar{n}$ and the incident wave vector in the direction of propagation $\bar{k}^i$ changes sign. This is referred to as self shadow. A point on the surface may also be shadowed by a topographical feature (hill) not immediately adjacent to it. Shadowing in this case is character-ized by the conditional probability P_2 (Sancer, 1969) that a point on the surface is

both visible at the receiver and illuminated by the source given the rough surface height and slope characteristics. When the full wave approach is used, self shadowing (which is accounted for intrinsically) is shown to have a significant effect on scattering. Using the physical optics solution or the small perturbation solution, the self shadowing function is ignored. This work on shadowing (which uses the full wave approach) also has a major impact on multiple (double) scatter (Bahar and El-Shenawee 1991a, b, 1994).

The full wave approach has been used to determine the bistatic reflection and transmission scattering cross sections of rough surfaces for all polarizations, frequencies and incident and scatter wave directions. Full wave expressions for vertically and horizontally polarized field intensities that are diffusely scattered *across* rough interfaces are needed in order to evaluate the backscattered intensities when scattering occurs at more than one interface. The Principal Investigator has conducted extensive work in this field (Bahar, 1988; Bahar and Fitzwater, 1989). This work on scattering upon transmission *across* a rough surface has been extended to two dimensionally rough surfaces and both the like and cross polarized scattering cross sections are accounted for in the analysis.

To enhance the potential applications of the full wave approach to remote sensing problems, computer codes have been developed to compute the sixteen elements of the backscatter Mueller matrix (Bahar and Kubik, 1989). This work has been used to determine the tilt modulation of the scattering cross sections (Bahar and Kubik, 1993a, 1993b). We propose to generalize this phase of our work in order to apply the full wave approach to broad range of polarimetric radars (Haugland et al., 1992).

III. OVERVIEW OF FULL WAVE APPROACH

Rigorous closed form solutions for the reflection and transmission of electromagnetic waves have been derived for multilayered dielectric structures of uniform thickness

11

(Wait, 1962). However, in a large variety of pertinent radio wave propagation problems the thicknesses of the layers are nonuniform and the height of the interface between two adjacent dielectric layers is a random variable. In these cases the incident waves are depolarized and scattered into both propagating and evanescent waves. Furthermore, an incident plane wave may be coupled into guided surface waves and lateral waves of the structure.

Often the problem that is actually solved is a highly idealized version of the original problem and concepts such as "effective dielectric coefficient" and "effective surface impedance" are introduced in order to make the solution of the original problem more tractable. However, the validity of such approximations is limited and they do not necessarily satisfy reciprocity.

Using a full wave approach, it is possible to analyze more realistic models of the original physical structure without introducing simplifying approximations that cannot be justified apriori (Bahar 1973a,b, 1974). The full wave approach is based on the expansion of the electromagnetic fields into a complete spectrum of vertically and horizontally polarized (propagating and evanescent) waves that include the radiation term, the lateral wave and the guided (surface) waves of the structure. Exact boundary conditions are imposed at each irregular interface of the structure and Maxwell's equations are converted into a rigorous set of coupled telegraphists' equations. To this end, precise mathematical procedures are followed and term by term differentiation of nonuniform convergent series is avoided. The coupled telegraphists' equations provide solutions for the forward and backward traveling complex wave amplitudes that are related to the electric and magnetic field transforms. Thus, both near field and far field solutions can be evaluated. The far fields scattered by the irregular layered structure can be evaluated in terms of the field transforms by using steepest descent techniques. This work has been significantly refined in recent years (Bahar 1991, Bahar and Lee 1994).

Maxwell's equations are converted into the following generalized telegraphists' equations for the forward and backward wave amplitudes a^P and b^P respectively (Bahar 1973a, b).

$$-\frac{da^P}{dx} - iua^P = \sum_Q \sum_{v'} \int \left(S_{PQ}^{BA} a^Q + S_{PQ}^{BB} b^Q \right) dw' - A^P,$$ (1)

and

$$-\frac{db^P}{dx} + iub^P = \sum_Q \sum_{v'} \int \left(S_{PQ}^{AA} a^Q + S_{PQ}^{AB} b^Q \right) dw' - B^P.$$ (2)

Explicit closed form expressions for the reflection and the transmission scattering coefficients S_{PQ}^{AB} have been derived (Bahar 1973b). Excitations of vertically and horizontally polarized waves are considered. The terms A^P and B^P appearing in (1) and (2) account for the electric and magnetic sources $\bar{J}, \rho$ and $\bar{M}, \rho_m$.

The first-order iterative solutions for the wave amplitudes a^P and b^P are obtained by neglecting the transmission and reflection scattering coefficients in (1) and (2). These first-order solutions for the primary fields are substituted on the right side of (1) and (2), and the resulting equations are solved to obtain the second order iterative solution for the wave amplitudes. These second-order iterative solutions are used in the complete expansions for the electromagnetic fields to obtain the desired iterative solutions for the scattered radiation fields through the use of the steepest descent method. Thus the first-order solutions to (1) and (2) are the primary vertically and horizontally polarized fields excited by the vertical electric and magnetic dipoles respectively. The second-order iterative solutions which account for depolarization and single scatter in arbitrary directions are suitable even when the rough surface slopes are not small (Bahar, 1981a). Since the full wave expressions for the fields are valid for all observation points, they can also be used to determine the fields near the surface. Thus the single scattered field that unpinges

13

upon the rough surface can be used to determine the double scattered field from rough surfaces (Bahar and El-Shenawee 1994).

The principal results are summarized here since some of the recent references are still in press. The expression for the vertically and horizontally polarized diffuse single scattered fields from the rough surface $y = h(x_s)$ are given by

$$E_S^{PF} = G_{00} \int S^{PP} \left[\exp(i_v^{\rightarrow} \cdot \bar{r}_s) - \exp(i_v^{\rightarrow} \cdot \bar{r}_t) \right] dx_s E^{Pi} = E^{Pf} - E_D^{Pf} \tag{3}$$

in which S^{PP} is the surface element scattering coefficient, $\bar{r}_s$ is the position vector to a point on the rough surface and $\bar{r}_t$ is its projection on the mean surface y = 0. The vector $\bar{v} = \bar{k}_o^f - \bar{k}_o^i$ where $\bar{k}_o^f$ and $\bar{k}_o^i$ are the scattered and incident wave vectors, k_o is the free space wave number and G_{00} is a constant. The zero order (quasi specular) scattered field E_D^{Pf} is not included in the expression for the diffuse scattered field (Rice 1951). Using (3) the corresponding expression for the ensemble average of the scatter cross sections per unit area are given by

$$< \sigma^P > = \left| S^{PQ}(\bar{n}^f, \bar{n}^i) \right|^2 Q(\bar{n}^f, \bar{n}^i) \tag{4}$$

For homogeneous isotropic rough surfaces

$$Q(\bar{n}^f, \bar{n}^i) = \frac{2k_0^4}{v_y^2} \int_o^\infty \left[X_2(v_y, -v) - |X(v_y)|^2 \right] J_o(v_{xz}\bar{r}_d) d\bar{r}_d \tag{5}$$

where $\bar{r}_d = \bar{r}_{t1} - \bar{r}_{t2}$ X and X_2 are the characteristic and joint characteristic functions. For the composite rough surfaces with large slopes, the scatter cross sections are obtained by viewing the surface as a superposition of arbitrarily oriented pixels. (Bahar et al 1983b). For each arbitrarily oriented pixel, the scatter cross section is given by

$$\langle \sigma^{PQ} \rangle_p = \left| D^{PQ} \right|^2 Q_p(\bar{n}^f, \bar{n}^i) \tag{6}$$

14

where D^{PQ} is the element of the scattering matrix D given by

$$D = T^f S_p T^i \qquad (7)$$

in which S_P^{PQ}, the elements of the 2x2 matrix S_p is obtained from S^{PQ} on replacing the angles of incidence and scatter in the reference coordinate system by the incident and scatter angles in the (local) pixel coordinate system and the 2x2 matrices T^i and T^f relate the vertically and horizontally polarized waves of the reference coordinate system (primed) to the vertically and horizontally polarized waves of the pixel (unprimed) coordinate system. Furthermore,

$$Q_p(\bar{n}^f, \bar{n}^i) = \frac{2k_0^4}{(\bar{a}_y' \cdot \bar{a}_y)^2 v_y^2} \int_o^\infty \left[X_2(v_y, -v_y) - |X(v_y)|^2 \right] J_0(v_{xz} r_d) r_d dr_d \qquad (8)$$

The scatter cross section for the composite rough surface is obtained by summing the radar cross sections of the individual pixels. Thus if the slopes of each pixel is also random (with probability density function $p(h_x, h_z)$, the scatter cross section (per unit area) for the composite rough surface $\langle \sigma^{PQ} \rangle_C$ is given by the statistical average of the pixel scatter cross section per unit area

$$\langle \sigma_c^{PQ} = \langle \left| D^{PQ} \right|^2 Q_P(\bar{n}^f, \bar{n}^i \rangle \qquad (9)$$

The surface height autocorrelation function for the pixel is

$$\langle h_{S1}, h_{S2} \rangle = \langle h_S^2 \rangle R_S(r_d) = 2\pi \int_{kd}^{kc} \frac{W(k)}{4} J_0(k r_d) k dk \qquad (10)$$

and the total mean square slope of the pixel is

$$J_S^2 = 2\pi \int_0^{k_d} \frac{W(k)}{4} k^3 dk \qquad (11)$$

where $k_d = 2\pi/L_P$ (L_P is the lateral dimension of the pixel) k_c is the cut off wave number (Brown, 1978) and W(k) is the surface height spectral density function.

15

It is readily shown that when the surface heights and slopes are of the same order of smallness the full wave solution (4) reduces to the small perturbation solution.

A third order iterative solution to the generalized telegraphists equations (1), (2) has also been carried out in order to obtain the full wave results for the multiple (double) scattered field (Bahar and El-Shenawee 1993, 1994).

IV. ENHANCED BACKSCATTER

Enhanced backscatter from rough surfaces has been observed in numerous carefully conducted experiments. While the original measurements of backscatter enhancement were conducted using two dimensionally rough surfaces, no numerical or analytical solutions for the scattered electromagnetic fields were available. Thus it was not possible to conduct a parametric study of the observed phenomena and to physically interpret them. More recently, experimental, numerical and analytical investigations have been carried out on surfaces that are essentially rough in only one dimension. The plane of incidence was restricted to the plane in which the local normal to the rough surfaces lies. Thus these surfaces do not depolarize the incident waves and the problem is essentially scalarized. While these one dimensional rough surfaces do not have the same range of physical applications as the two dimensional rough surfaces, the numerical and analytical solutions to the electromagnetic scattering problem for the one dimensional rough surfaces are easier to interpret.

This intermediate step provides the necessary impetus to return to the hitherto intractable (both numerically and analytically) problem of electromagnetic scattering from two dimensionally rough surfaces. To date no comprehensive computer code can be used to solve the problem of scattering from two dimensionally rough surfaces numerically (moment methods) in a tractable manner. Computers are used

to conduct a complete parametric study of the scattering phenomena. This parametric study involves the determination of the effects of changing the statistical characterizations of the rough surface upon the enhanced backscatter phenomena. The random rough surface is characterized by the joint surface height/slope probability density function at two points on the surface (including the mean square height and slope, the surface height autocorrelation function, and the correlation length). The effects of changing the incident angle, the polarization of the incident and scattered waves, and the medium parameters are studied. The research was initially restricted to the derivation of high frequency physical optics approximations since it sheds light on the analytical and numerical solutions to the problem. The precise level of the polarimetric backscattered intensities (the Stokes vectors related by the Mueller matrix), as well as the range of angles about the backscatter direction for which the observed enhanced backscattered is significant is studied in detail.

V.   OUTLINE OF APPROACH FOR DOUBLE SCATTER CROSS SECTIONS AND SUMMARY OF MOST IMPORTANT RESULTS

The expressions for the vertically and horizontally polarized diffuse single scattered radiation fields from the two-dimensionally rough surface $y_s = h(x_s, z_s)(-L < x_s, z_s < L)$ are given in matrix form as follows:

$$G_s^f(\bar{r}) = (\frac{k_o}{2\pi i})^2 \int \int S(\bar{k}', \bar{k}^i) \exp(-i\bar{k}' \cdot \bar{r})$$
$$\left[\frac{\exp(iv' \cdot \bar{r}_s - \exp(i\bar{v}' \cdot \bar{r}_t)}{v_y'} \right] dx_s dz_s \frac{dk'_{oy} dk'_{oz}}{k'_{ox}} G^i(o) \tag{12}$$

in which G_s^f and G^i are 2×1 matrices whoe elements are the vertically and horizontally polarized components of the scattered and incident fields E^{pf} and $E^{Pi}(P = V, H)$ respectively. The elements of the 2×2 scattering matrix $S(\bar{k}', \bar{k}^i)$ are the like-and cross-polarized scattering coefficients $S^{PQ}(P, Q = V, H)$. These

17

coefficients are functions of the incident and scatter wave vectors $\bar{k}_o^i = k_o \bar{n}^i$ and $\bar{k}_o' = k_o \bar{n}'$ respectively and the electromagnetic parameters of the media on both sides of the rough interface (Bahar and Lee 1994). The position vectors to the observation point and to a point on the rough surface are $\bar{r}$ and $\bar{r}_s$ respectively and $\bar{r}_t$ is the projection of $\bar{r}_s$ on the mean plane $y = 0$. The vector $\bar{v}$ is given

$$\bar{v}' = \bar{k}_o' - \bar{k}_o^i = v_x \bar{a}_y + v_y \bar{a}_y + v_z \bar{a}_z \tag{13}$$

The integration in (3) is over the rough surface variables x_s and z_s and the wave vector variables k_{oz}' and k_{oy}'. In (3) $\exp(i\omega t)$ time excitations are assumed. Note that the expression for G_s^f remains finite as $v_y' \to 0$ (grazing incident and scatter angles).

For simplicity we initially consider one-dimensional rough surfaces $y = h(x_s)$. The incident and wave vectors lie in the x, y plane and there is no depolarization $S^{PQ}(\bar{k}, \bar{k}^i) \to O(P \neq Q)$. In this case the vertically and horizontally polarized waves are uncoupled and the scattering problem is scalarized. Thus equation (12) can be expressed as follows:

$$G_s^{fP}(\bar{r}) = \frac{-k_o}{2\pi} \int_{n'=-\infty}^{\infty} \int_{x_s=-L}^{L} S^P(\bar{k}'\bar{k}^i)\exp(-i\bar{k}_o'.\bar{k}_o^i)$$
$$\left[\frac{\exp(i\bar{v}' \cdot \bar{r}_s) - \exp(i\bar{v}' \cdot \bar{r}_s) - \exp(i\bar{v}' \cdot \bar{r}_t)}{v_y'}\right] U(\bar{r}_s)dx_s' \frac{dk_{oy}'}{k_{ox}'} G^{ip}(o), \ P = V, H \tag{14}$$

in which $U(\bar{r}_s)$ is a shadow function (Sancer 1969). Equation (14) is used to obtain the differential wave vector contribution to the diffuse single scatter field that impinges on the surface at $\bar{r}_{s2}(\bar{r}_s \to \bar{r}_{s1})$ and $(\bar{r} \to \bar{r}_{s2})$. This expression is used in (14) instead of the incident plane wave G^{iP} and the expression for the double scattered field is obtained (Bahar and El-Shenawee 1944). Use is made of the steepest descent method to obtain the far field expression for the double scattered field in the

direction of the wave vector $\bar{k}_0^f = k_o \bar{n}^f$.

$$G_d^{fP}(\bar{r}) = \frac{k_o^4}{4\pi^2}\sqrt{\frac{2\pi}{k_o r}}e^{i\pi/4}e^{ik_o r}\int_{n_y'=-1}^{1}\int_{x_{s2}'=-L}^{L}S_{2l}^P(\bar{k}^f,\bar{n}') \times$$

$$\exp\{-ik_o x_{s1}'(n_x^i - n_x')\}\exp\{ik_o x_{s2}'(n_x^f - n_x')\}\frac{\left[\exp(-ik_o h(x_{s1}')(n_y^i - n_y')) - 1\right]}{\left[k_o(-n_y^i + n_y')\right]} \times$$

$$\frac{\left[\exp\{ik_o h(x_{s2}')(n_y^f - n_y')\} - 1\right]}{\left[k_o(n_y^f - n_y')\right]}U(\bar{r}_{s1}')U(\bar{r}_{s2})dx_{s1}'dx_{s2}'\frac{dn_y'}{n_x'}G^{iP}(0) \tag{15}$$

The expression for the double scattered field (14) is multiplied by its complex conjugate to obtain the expression for the double scatter power. After tedious manipulation of the expression for the scattered power (and accounting for the height-slope correlations [Bahar 1991]) it is shown that the (mean)diffuse scatter cross section per unit area can be expressed as follows for the quasi parallel scattering path $n_x' = \sqrt{1 - n_y'^2}, n_x'' = \sqrt{1 - n_y''^2}$ and $n_x' = -\sqrt{1 - n_y'^2}, n_x'' = -1\sqrt{1 - n_y''^2}$ (Bahar and El-Shenawee 1994).

$$\langle\sigma_{pd}\rangle = \frac{2k_o L_m}{2\pi^2}(2L_m)P_2(\bar{n}^i)P_2(\bar{n}^f)\int_{n_{dy}}\int_{n_{ay}}\langle\sigma_{pd1}(n_y', n''y)\rangle\langle\sigma_{pd2}(n_y', n''y))\rangle$$

$$\times[1 - P_2(|n_y'|)]\text{sinc}\{k_o L_m n_{dx}\}\exp(-k_o^2\langle h^2\rangle n_{dy}^2)\frac{dn_{ay}}{\sqrt{1 - (n_y')^2}}\frac{dn_{dy}}{\sqrt{1q - (n_y'')^2}} \tag{16}$$

where L_m is the width of a typical depression on the rough surface, $<\sigma_{pdq}(n_y', n_y'') >$ and $<\sigma_{pd2}(n_y', n_y'')$ are associated with single scatter cross sections and P_2 are the shadow functions (Sancer 1969). The vectors $\bar{n}_a$ and $\bar{n}_d$ are defined as

$$\bar{n}_a = \frac{\bar{n} + \bar{n}''}{2} \qquad \bar{n}_d = \bar{n}' - \bar{n}'' \tag{17}$$

The major contribution to the integral (16) is around $\bar{n}_d = \bar{O}$ for the quasi parallel case due to the interaction terms (between the single scatter cross sections $< \sigma >_{pd1}$ and $< \sigma_{pd2} >$) $\text{sinc}(k_o L_m n_{dx})\exp(-k_o^2 < h^2 > n_{dy}^2)$ in the integral (16).

The expression for the diffuse double scatter cross section associated with the quasi antiparallel paths $(n_x' = \sqrt{1 - n_y'^2}, n_x'' = -\sqrt{1 - n_y''^2}$ and $n_x' = -\sqrt{1 - n_y'^2}, n_x'' =$

$\sqrt{1 - n_y''^2}$) can be expressed as follows:

$$\langle \sigma_{ad} \rangle = \frac{2k_o L_m}{2\pi^2} P_2(\bar{n}^i) P_2(\bar{n}^f) \int_{n_{ay}} \int_{n_{ay}} \langle \sigma_{ad1}(n_y', n''y) \rangle \langle \sigma_{ad2}(n_y', n''y) \rangle \times$$

$$[1 - P_2(|n_y'|)][1 - P_2(|n_y''|)] \text{sinc}[k_o L_m(n_x^f + n_x^i - 2n_{ax})]$$

$$\exp[-k_o^2 \langle h^2 \rangle (n_y^f + n_y^i - 2n_{ay})^2] \frac{dn_{dy}}{\sqrt{1 - (n_y')^2}} \frac{dn_{ay}}{\sqrt{1 - (n_y'')^2}} \quad (18)$$

In (18) $\langle \sigma_{ad1}(n_y', n_y'') \rangle$ and $\langle \sigma_{ad2}(n_y', n''y) \rangle$ are associated with single scatter cross sections. In (16) and (17), the region of integration is half the diamond shaped area with end points on the n_{ay} axis at $(-1, 1)$ and on the n_{dy} axis at $(-2, 2)$. The major contributions to the integral (18) is around $\bar{n}_a = \bar{O}$. Due to the interaction terms $\text{sinc}[k_o L_m(n_x^f + n_x^i - 2n_{ax})] \exp(-k_o^2 \langle h^2 \rangle (n_y^f + n_y^i - 2n_{ay})^2]$ there is a sharp peak in the expression for $\langle \sigma_{pd} \rangle$ for the backscatter direction $\bar{n}^f = -\bar{n}^i$ (enhanced backscatter).

A comprehensive parametric study has been conducted to determine the dependence of the level and the angular width of the sharp enhanced backscatter upon the rough surface characteristics (mean square height $\langle h^2 \rangle$ and slope $\langle h_x^2 \rangle$ and the mean width of a typical depression L_m) (Bahar and El-Shenawee 1994). A high frequency stationary phase (specular point approximation of the full wave results) has also been obtained. These significantly simplified expressions shed light on the physical interpretation and the numerical evaluation of the double scatter cross section. However, it is shown that these high frequency results are practically independent of polarization for highly conducting surfaces. The angular width of the enhanced backscatter cross section is also narrower when the high frequency approximations are used.

We now turn to multiple scatter from the more general and interesting two dimensionally rough surfaces. Proceeding as in the case of the one dimensional rough surface, the expression for the double scattered far field is expressed as follows:

$$G_s^{fP}(\bar{r}_s) = (\frac{-k_o}{2\pi i})^3 \frac{\exp(-ik_o r)}{r} \int S_{2'}(\bar{n}^f, \bar{n}^i) \exp(ik_o \bar{n}^f \cdot \bar{r}_{s2}) \exp[-i\bar{k}' \cdot \bar{r}]$$

$$S_{1'}(\bar{n}', \bar{n}^i) \exp(-ik_o \bar{n}^i \cdot \bar{r}_{s1}') \frac{dn_y' dn_z'}{\sqrt{1 - n_y'^2 - n_z'^2}} dx_{s1}' dz_{s1}' dx_{s2}' dz_{s2}' G^i(o) \quad (19)$$

20

The expression for the diffuse double scattered intensity is obtained on multiplying (19) by its complex conjugate. Thus the diffuse double scatter cross sections $\langle \sigma_{pd} \rangle$ and $\langle \sigma_{ad} \rangle$ associated with the quasi parallel and quasi anti-parallel paths respectively can be expressed as follows:

$$
\begin{aligned}
\langle \sigma_{pd} \rangle &= \frac{8(2k_oL_m)^2}{2\pi^5} \int \int \int \int \langle \sigma_{pd1} \rangle \langle \sigma_{pd2} \rangle [1 - P_2(|n_y'|)][1 - P_2(|n_y''|)] \\
&\quad \text{sinc}(k_oL_mn_{dx})\text{sinc}(k_oL_mn_{dz})\exp(-k_o^2\langle h^2 \rangle n_{dy}^2 \\
&\quad \frac{dn_{ay}dn_{az}dn_{dy}dn_{dz}}{(1 - n_y'^2 - n_z'^2)[(1 - n_y''^2 - n_z''^2)]^{\frac{1}{2}}}
\end{aligned} \tag{20}
$$

in which L_m is the mean width of a typical depression on the surface and $\langle \sigma_{pd1} \rangle$ and $\langle \sigma_{pd2} \rangle$ are associated with single scatter cross sections for the quasi parallel paths. Furthermore

$$
\begin{aligned}
\langle \sigma_{ad} \rangle &= \frac{8(2k_oL_m)^2}{2\pi^5} \int \int \int \int \langle \sigma_{pd1} \rangle \langle \sigma_{pd2} \rangle [1 - P_2(|n_y'|)][1 - P_2(|n_y''|)] \\
&\quad \text{sinc}[k_oL_m(n_x^f + n_x^1 - 2n_{ax})]\text{sinc}[k_oL_m(n_z^f + n_z^1 - 2n_{az})]\exp[-k_o^2\langle h^2 \rangle \\
&\quad (n_y^f + n_y^i - 2n_{ay}^2)]\frac{dn_{ay}dn_{az}dn_{dy}dn_{dz}}{(1 - n_y'^2 - n_z'^2)[(1 - n_y''^2 0 - n_z''^2)]^{\frac{1}{2}}}
\end{aligned} \tag{21}
$$

In (21) $\langle \sigma_{ad1} \rangle$ and $\langle \sigma_{ad2} \rangle$ are associated with single scatter cross sections for the quasi antiparallel paths. In (20) and (21) the regions of integration are half the diamond shaped areas with end points on the n_{ay} axis at (-1, 1) and on the n_{dy} axis at (-2, 2) and on the n_{az} axis at (-1, 1) and on the n_{dz} axis at (-2, 2) (Bahar and El-Shenawee, 1994).

In equation (20) in view of the interaction terms between the single scatter cross section, $\text{sinc}(k_oL_mn_{dx})$ $\text{sinc}(k_oL_mn_{dz})\exp[-k_o^2\langle h^2 \rangle n_{dy}^2]$, the major contribution to the integral is around $\bar{n}_d = \bar{O}$ for the quasi parallel paths. Similarly in equation (21) in view of the interaction terms between the single scatter cross sections sinc $[k_oL_m(n_x^f + n_x^i - 2n_{ax})]$ sinc $[k_oL_m(n_z^f + n_z^i - 2n_{az}]$ exp $[-k_o^2 \langle h^2 \rangle (n_y^f + n_y^i - 2n_{ay})^2]$

and the shadow functions $[1 - P_2(|n\prime_y|)] \, [1 - P_2(|n\prime\prime_y|)]$ the major contribution to the integral is around $\bar{n}_a = \bar{O}$ for the quasi antiparallel paths.

Using the high frequency approximations, the cross sections associated with the single scatter $\langle \sigma_{pd1} \rangle$, $\langle \sigma_{pd2} \rangle$, $\langle \sigma_{ad1} \rangle$ and $\langle \sigma_{ad2} \rangle$ can be expressed in closed form and the resulting expressions for the double scatter cross section can be expressed in terms of four dimensional integrals. Developing an efficient computer code for equations (20) and (21) in the high frequency limit is in progress. The results sheds light on the physical interpretation and on the numerical evaluation of the full wave double scatter cross section in a tractable manner as in the case of the one dimensionally rough surface (Bahar and El-Shenawee, 1994). See page 21a.

VI. REFERENCES

1. Bahar, E. (1973a), "Depolarization of electromagnetic waves excited by distributions of electric and magnetic sources in inhomogeneous multilayered structures of arbitrarily varying thickness. Generalized field transforms," J. Math. Phys., Vol. 14, No. 11, pp. 1502-1509.

2. Bahar, E. (1973b), "Depolarization of electromagnetic waves excited by distributions of electric and magnetic sources in inhomogeneous multilayered structures of arbitrarily varying thickness. Full wave solutions," J. Math. Phys., Vol. 14, No. 11, pp. 1510-1515.

3. Bahar, E. (1974), "Depolarization in Nonuniform Multilayered Structures-Full Wave Solutions," J. Math. Phys., Vol. 15, No. 2, pp. 202-208.

4. Bahar, E. (1981a), "Full-Wave Solutions for the Depolarization of the Scattered Radiation Fields by Rough Surfaces of Arbitrary Slope," IEEE Transactions on Antennas and Propagation, Vol. AP-29, No. 3, pp. 443-454.

5. Bahar, E. (1981b), "Scattering Cross Sections for Composite Random Surfaces-Full Wave Analysis," Radio Science. Vol. 16. No. 6, pp. 1327-1335.

6. Bahar, E. (1988), "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media," Radio Science. Vol. 23, No. 5, pp. 749-759.

7. Bahar, E. (1991), "Full Wave Analysis for Rough Surface Diffuse, Incoherent Radar Cross Sections with Height-Slope Correlations Included," IEEE Transactions on Antennas and Propagation, Vol. AP-39, No. 9, pp. 1293-1304.

8. Bahar, E. and D. E. Barrick (1983), "Scattering Cross Sections for Composite Surfaces that Cannot be Treated as Perturbed Physical Optics Problems," Radio Science, Vol. 18, No. 2, pp. 129-137.

9. Bahar, and M. El-Shenawee (1991a), "Single and Multiple Scatter and Depolarization from Two Dimensional Rough Surfaces," Proceedings of the IEEE-AP-S International Symposium and URSI Radio Science Meeting, London, Ontario, Canada, June 24-28, 1991.

10. Bahar, and M. El-Shenawee (1991b), "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," IEEE Transactions on Magnetics, Vol. 27, No. 5, pp. 4287-4290, December 1991.

11. Bahar E. and M. El-Shenawee (1993), "Full Wave Multiple scatter from One Dimensional Rough Surfaces," Proceedings of the IEEE Antennas and Propagation Society International Symposium, pp. 1316-1219, July 1993.

12. Bahar, E. and M. El-Shenawee (1994), "Vertically and Horizontally Polarized Diffuse Multiple Scatter Cross Sections of One Dimensional Random Rough Surfaces that Exhibit enhanced backscatter-Full Wave Solutions," Journal of the Optical Society of America, in press.

13. Bahar, E., D.E. Barrick and M.A. Fitzwater (1983a), "Computations of Scattering Cross Sections for Composite Surfaces and the Specification of the Wavenumber Where Spectral Splitting Occurs," IEEE Transactions on Antennas and Propagation, Vol. AP-31, No. 5, pp. 678-709.

14. Bahar, E., D.E. Barrick, C.L. Rufenach and M.A. Fritzwater (1993b), "Scattering Cross Section Modulation for Arbitrary Oriented Composited Rough Surfaces-Full Wave Solutions," Radio Science, Vol. 18, No. 5, pp. 675-690.

15. Bahar, E. and M.A. Fitzwater (1984), "Scattering Cross Sections for Composite Rough Surfaces Using the Unified Full Wave Approach," IEEE Transactions on Antennas and Propagation, Vol. AP-32, No. 7, pp. 730-734.

16. Bahar, E. and M. A. Fitzwater (1985), "Like and Cross-Polarized Scattering Cross Sections for Random Rough Surfaces: Theory and Experiment," Journal of the Optical Society of America, A, Vol. 2, pp. 2295-2303.

17. Bahar, E. and M.A. Fitzwater (1989), "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," IEEE Transactions on Antennas and Propagation, AP-S Vol. 37, No. 12, pp. 1609-1616.

18. Bahar, E. and S.M. Haugland (1994), "Unified full wave solutions to Interpret Apollo Lunar Surface Data," Transactions on Geoscience and Remote Sensing, No. 1, pp. 72-77.

19. Bahar, E. and R. Kubik (1989), "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-0, Vol. 3, pp. 1296-1299.

20. Bahar, E. and R. Kubik (1993a), "Simulation of High Resolution Radar Polarimetric Images - Unified Full Wave Approach," International Journal of Remote Sensing, Vol. 14, No. 15, pp. 2829-2845.

21. Bahar, E. and R. Kubik (1993b), "Tilt Modulation of High Resolution Radar Backscatter Cross Sections Unified Full Wave Approach," Transactions on Geoscience and Remote Sensing, Vol. 31, No. 6, pp. 1229-1242.

22. Bahar, E. and B.S. Lee (1994a), "Full wave Solutions for Rough Surface Backscatters Radar Cross Sections - Comparison with Small Perturbation, Physical Optics Numerical and Experimental Results," Radio Science, Vol. 29, No. 2, pp. 407- 429, March/April 1994.

23. Barrick, D.E. and W.H. Peake (1968), "A Review of Scattering from Surfaces with Different Roughness Scales," Radio Science, Vol. 3, No. 8, pp. 865-868.

24. Beckmann, P. (1968), The Depolarization of Electromagnetic Waves, Golem Press, Boulder, Colorado.

25. Beckmann, P. and A. Spizzichino (1963), The Scattering of Electromagnetic Waves from Rough Surfaces, MacMillan, New York.

26. Brown, G. S. (1978), "Backscattering from a Gaussian Distributed Perfectly Conducting Rough Surface," IEEE Transactions on Antennas and Propagation, Vol. AP-26, No. 3, pp. 472-82.

25

27. Daley, J. C., W. T. Davis and N. R. Mills (1970), "Radar Return in High Sea States," Naval Research Laboratory Report 7142, U. S. Government Printing Office, Washington, D.C.

28. Haugland, S. M., E. Bahar and A. H. Carrieri (1992), "Identification of Contaminant Coatings over Rough Surfaces Using Polarized IR Scattering," Applied Optics, Vol. 31, No. 19. pp. 3847-3852.

29. Knots, M.E., T.R. Michel and K.A. O'Donnell (1993), "Comparison of Theory and Experiment in Light Scattering from a Randomly Rough Surface," Journal of the Optical Society of America, A. Vol. 10, No. 10, No. 5, pp. 928-941.

30. Rice, S. O. (1951), "Reflection of Electromagnetic Waves from a Slightly Rough Surface," Communication of Pure and Applied Math., Vol. 4, pp. 351-378.

31. Sancer, M.I., (1969), "Shadow Corrected Electromagnetic Scattering from a Randomly Rough Surface," IEEE Transactions on Antennas and Propagation, Vol. AP-17, pp. 577-585.

32. Valenzuela, G. R. (1968), "Scattering of Electromagnetic Waves from a Tilted Slightly Rough Surface," Radio Science, Vol. 3, No. 11, pp. 1051-1066.

33. Wait, J. R. (1962), Electromagnetic Waves in Stratified Media, MacMillan, New York.

34. Wright, J. W. (1968), "A New Model for Sea Clutter," IEEE Transactions on Antennas and Propagation, Vol. AP-16, No. 2, pp. 217-223.

VII. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES EARNED BY THEM

In addition to the principal investigator, Ezekiel Bahar, the main contributors to this research project are Magda El-Shenawee (Ph.D. Candidate/Research Associate), and M.S. and Ph.D. students.

During this reporting period, the following students received their M.S. and Ph.D. degrees in Electrical Engineering. Copies of their theses were submitted with the Semi-Annual/Annual Progress Reports.

(i) Magda Osman El-Shenawee, Ph.D. Thesis, "Full Wave Multiple Scattering and Depolarization of Electromagnetic Fields From Rough Surfaces."

(ii) Bom Son Lee, M.S. Thesis, "Radar Cross Sections for Random Rough Surfaces Using Full Wave Approach with Height/Slope Correlations Included."

(iii) Robert D. Kubik, Ph.D. Thesis, "Scattering and Depolarization Upon Transmission Across and Multiple Reflection from Irregular Multilayered Structures."

Theses in Project:

(i) Y. Zhang, Topic of Ph.D. Thesis: "Numerical Solutions for the Scattered Fields from Rough Surfaces Using the Full Wave Generalized Telegraphist's Equations" (Expected date of completion: December, 1994).

(ii) S. Shi, Topic of Ph.D. Thesis: "Scattering from Surfaces with Multiple Scales of Roughness" (Expected date of completion: December, 1994).

(iii) Bom Son Lee, Topic of Ph.D. Thesis: "Scattering and Depolarization of Electromagnetic Waves upon Reflection and Transmission from Rough Surfaces–Full Wave Solutions with Height/Slope Correlations Included" (Expected date of completion: May, 1995).

VIII. LIST OF MANUSCRIPTS SUBMITTED AND PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES

A. Papers Presented at Technical Meetings

1. IEEE-AP-S International Symposium and URSI Radio Science Meeting, London, Ontario, Canada, June 24-28, 1991, "Single and Multiple Scatter and Depolarization from Two Dimensional Rough Surfaces," with M. El-Shenawee.

2. Progress in Electromagnetic Research Symposium, MIT, Cambridge, MA, July 1-5, 1991, "Two-Dimensional Random Rough Surfaces that Exhibit Uniform Enhanced Backscatter for V and H Polarizations Over a Very Wide Range of Incident Angles," with R.D. Kubik.

3. 1991 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 24-28, 1991, "Mueller Matrix Elements for Optically Thin Chemical Coating Layers Over Rough Surfaces," with S.M. Haugland and A.H. Carrieri.

4. Topical Meeting of the International Commission for Optics, Atmospheric, Volume and Surface Scattering and Propagation, Florence, Italy, August 27-30, 1991, "Single and Multiple Scatter from Random Rough Surfaces, Full Wave Solutions," with R.D. Kubik and M. El-Shenawee.

5. Advisory Group for Aerospace Research and Development, Fall 1991, Electromagnetic Wave Propagation Panel Symposium on Remote Sensing of the Propagation Environment, Cesme, Turkey, September 30 - October 4, 1991, "Active Remote Sensing of the Ionosphere and the Earth Surface Irregularities."

6. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 7-11, 1992, "Diffuse Incoherent Radar Group Cross Sections for Random Rough Surfaces with Height-Slope Correlations, Included."

7. Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, Boulder, CO, January 14-16, 1992, "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments, Unified Full Wave Approach," with R.D. Kubik.

8. 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting, Houston, TX, May 26-29, 1992, "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film," with R.D. Kubik.

9. Advisory Group on Aerospace Research and Development (AGARD), Electromagnetic Wave Propagation Panel, 50th Symposium on Radio Location Techniques, June 1-5, 1992, London, England, "Irregular Media Effects on Radiowave Signals Used in Navigation and Positioning Systems."

10. 1992 IEEE-APS International Symposium and URSI Radio Science Meeting, July 20-24, 1992, Chicago, IL, "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee.

11. URSI International Symposium on Electromagnetic Theory, Sydney, Australia, August 17-20, 1992, "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics."

12. 1992 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 22-25, 1992, "Use of a New Polarimetric Optical Bistatic

Scatterometer to Measure the Transmission and Reflection Mueller Matrix for Arbitrary Incident and Scatter Direction."

13. First International Conference on Planetary Systems: Formation. Evolution and Detection, California Institute of Technology, <u>Pasadena</u>, <u>CA</u>. December 8-10, 1992, "Full Wave Solutions to Interpret Planetary Surface Data," with M. Haugland.

14. International Union of Radio Science (URSI) Meeting, University of Colorado, <u>Boulder</u>, <u>CO</u>, January 5-8, 1993, "Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces - Full Wave, Perturbation and Physical Optics Solutions," with B.S. Lee.

15. 24th Annual Lunar and Planetary Science Conference, <u>Houston</u>, <u>Texas</u>. March 15-19, 1993, "Interpretation of Lunar and Planetary Electromagnetic Scattering Using the Full Wave Solutions," with M. Haugland.

16. Progress in Electromagnetic Research Symposium, PERS 1993, California Institute of Technology, <u>Pasadena</u>, <u>California</u>, July 12-16, 1993, "Multiple Scattering From One Dimensional Random Rough Surfaces - Full Wave Solution," with M. El-Shenawee.

17. Progress in Electromagnetic Research Symposium, PERS 1993, California Institute of Technology, <u>Pasadena</u>, <u>California</u>, July 12-16, 1993, "Numerical Solutions of Scattered Fields from Rough Surfaces Using Full Wave Generalized Telegraphists' Equations with Y. Zhang.

18. 1993 IEEE-APS International Symposium and Radio Science Meeting, University of Michigan, <u>Ann Arbor</u>, <u>Michigan</u>, June 27 - July 2, 1993, "Full Wave Multiple Scattering from One Dimensional Random Rough Surfaces and High Frequency Stationary Phase Approximations," with M. El-Shenawee.

30

19. XIVth General Assembly of International Union of Radio Science, Commission F Session on Depolarization Due to Rain, Ice and Surface Scattering, Kyoto, Japan, August 25 - September 2, 1993, "Tilt Modulation of Like Polarized and Depolarized Cross Sections Used to Characterize Non-Gaussian Rough Surfaces," with R.D. Kubik and Y.F. Li.

20. 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, Tokyo, Japan, August 18-21, 1993, "High Frequency Approximations to Multiple Scatter by Rough Surfaces that Exhibit Enhanced Backscatter," with M. El-Shenawee.

21. 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, Tokyo, Japan, August 18-21, 1993, "Backscatter Mueller Matrix Elements for Irregular Stratified Media," with R.D. Kubik.

22. The Third International Symposium on Antennas and EM Theory, Nanjing, China, September 6-9, 1993, "Comparison of Two Interature Solutions with Numerical Solutions for Rough Surface Scattering Using the Generalized Telegraphists' Equations," with Y. Zhang.

23. Conference on the Computation of Electromagnetic Fields, Miami, Florida, October 31 - November 1, 1993, "Numerical Method to Compute TE and TM Multiple Scatter from Rough Surfaces Exhibiting Backscatter Enhancement," with M. El-Shenawee.

24. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder Colorado, January 5-8, 1994, "Beckmann's Construction of Non-Gaussian Two-Dimensional Probability Density Functions from their Marginals and Correlation Coefficients."

25. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder Colorado, January 5-8, 1994, "Radar Scatter Cross Sections for Two Dimensional Random Rough Surfaces that Account for Height/Slope Correlations," with B.S. Lee.

26. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder Colorado, January 5-8, 1994, "Full Wave Solutions of Electromagnetic Waves Scattered from Irregular Stratified Media," with Y. Zhang.

27. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder Colorado, January 5-8, 1994, "Predictions of the Ellipsometric Parameters of Multilayered Structures," with R.D. Kubik.

28. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder Colorado, January 5-8, 1994, "High Frequency Approximations for the Multiple Scatter Cross Sections of One and Two Dimensional Random Rough Surfaces," with M. El-Shenawee.

29. 1994 IEEE AP-S International Symposium and URSI Radio Science meeting, University of Washington, Seattle, Washington, June 19-24, 1994, "Radar Cross sections for two dimensional random rough surfaces with different roughness scales," with B.S. Lee.

30. 1994 IEEE AP-S International Symposium and URSI Radio Science meeting, University of Washington, Seattle, Washington, June 19-24, 1994, "Backscatter modified Mueller Matrix Elements for Stratified Medium," with R.D. Kubik.

31. 1994 IEEE AP-S International Symposium and URSI Radio Science meeting, University of Washington, Seattle, Washington, June 19-24, 1994, "Examination of large radius of curvature approximation for rough surface scatter cross sections," with M. El-Shenawee.

32. 1994 International Geoscience and Remote Sensing Symposium IGARSS'94, California Institute of Technology, <u>Pasadena</u>, <u>California</u>, August 8-12, 1994, "Multiple Scattering from Random Rough Surfaces Based on a Deterministic Full Wave Model," with M. El-Shenawee.

33. 1994 International Geoscience and Remote Sensing Symposium IGARSS'94, California Institute of Technology, <u>Pasadena</u>, <u>California</u>, August 8-12, 1994, "Full Wave Scatter Cross Sections for Two Dimensional Random Rough Surfaces Using Joint Conditional Surface Height Characteristic Functions," with B.S. Lee.

B. Papers Published in the Technical Literature

1. "Full Wave Analysis for Rough Surface Diffuse, Incoherent Radar Cross Sections with Height-Slope Correlations Included," *IEEE Trans. on Antennas and Propagation*, Vol. 39, No. 9, pp. 1293-2304, September 1991.

2. "Unified Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland, *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 32, No. 1, pp. 72-77, January 1994.

3. "Tilt Modulation of High Resolution Radar Backscatter Cross Sections: Unified Full Wave Approach," with R. D. Kubik, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 31, No. 6, pp. 1229-1242, November 1993.

4. "Simulation of High Resolution Radar Polarimetric Images - Unified Full Wave Approach," with R. D. Kubik, *International Journal of Remote Sensing,* Vol. 14, No. 15, pp. 2829-2845, 1993.

5. "Scattering Cross Sections of Non-Gaussian Rough Surfaces: Unified Full Wave Approach," with Y. F. Li, *IEEE Transactions on Antennas and Propagation*, Vol. 39, No. 12, pp. 1777-1781, December 1991.

6. "Application of Tilt Modulation of the Scatter Cross Sections to Distinguish Between Different Non-Gaussian Rough Surfaces Unified Full Wave Approach," with R.D. Kubik and Yang-Feng Li, *International Journal of Remote Sensing*, Vol. 15, No. 6, pp. 1317-1334, 1994.

7. "Identification of Contaminant Coatings Over Rough Surfaces Using Polarized IR Scattering," with S. M. Haugland and A.H. Carrieri, *Applied Optics*, Vol. 31, No. 19, pp. 3847-3852, July 1, 1992.

8. "Examination of Full Wave Solutions and 'Exact Numerical Results' for One-Dimensional Slightly Rough Surfaces," *Journal of Geophysical Research*, Vol. 96, No. C9, pp. 17,123-17,131, Sept. 15, 1991.

9. "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee, *Proceedings of the Fourth Biennial IEEE Conference on Electromagnetic Field Computation AP-S*, Toronto, Ontario Canada, October 24, 1990.

10. "Single and Multiple Scatter and Depolarization from Two-Dimensional Rough Surfaces," with M. El-Shenawee, *Proceedings of the IEEE 1991 International Symposium AP-S*, London, Ontario, Canada, June 24-28, 1991.

11. "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee, *IEEE Trans. on Magnetics*, Vol. 27, No. 5, pp. 4287-4290, September 1991.

12. "High Resolution Radar Polarimetric imaging of the Ocean Surface Due to Tile Modulation - Unified Full Wave Approach," with R. D. Kubik, *Proceedings of IGARSS'91 on Remote Sensing: Global Monitoring for Earth Management*, Espoo, Finland, Vol. 1, p. 2017-2020, 1991.

13. "Full Wave Solutions for Mueller Matrix Elements Used to Remotely Sense Irregular Stratified Structures," with S. Haugland, and A. Carrieri, *Proceedings of IGARSS'91 on Remote Sensing: Global Monitoring for Earth Management,* Espoo, Finland, Vol. 1, p. 1479-1482, 1991.

14. "Active Remote Sensing of the Ionosphere and the Earth Surface Irregularities," *Proceedings of the 49th AGARD-EPP Symposium on Remote Sensing of the Propagation Environment,* Cesme, Turkey, 1991.

15. "Polarized IR Scattering Used to Identify Contaminant Coatings over Rough Surfaces," *Proceedings of the 1991 Scientific Conference on Obscuration and Aerosol Research,* in press, June 1991.

16. "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments: Unified Full Wave Approach," with R. D. Kubik, *Proceedings of the Specialist Meeting on Microwave Radiometry and Remote Sensing Applications,* June 1992.

17. "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee, *Proceedings of the 1992 Antennas and Propagation Society International Symposium,* in press July 1992.

18. "Irregular Media Effects on Radiowave Signals Used in Navigation and Positioning Signals," *Proceedings of the Advisory Group on Aerospace Research and Development (AGARD) Electromagnetic Wave Propagation Panel, 50th Symposium on Radio Location Techniques,* June 1992.

19. "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film of Oil," with R. D. Kubik, *Proceedings of the 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting,* June 1992.

20. "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics," *Proceedings of the 1992 International Union of Radio Science (URSI) Symposium on Electromagnetic Theory*, Sydney, Australia, August 1992.

21. "High Frequency Approximations to Multiple Scatter by Rough Surfaces that Exhibit Enhanced Backscatter," with M. El-Shenawee, *Proceedings of the 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting*, August 1993.

22. "Backscatter Mueller Matrix Elements for Irregular Stratified Media," with R.D. Kubik, *Proceedings of the 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting*, August 1993.

23. "Comparison of Two Iterature Solutions with Numerical Solutions for Rough Surface Scattering Using the Generalized Telegraphist's Equations," with Y. Zhang, *Proceedings of the Third International Symposium an Antennas and EM Theory*, September 1993.

24. "Numerical Method to Compute TE and TM Multiple Scatter from Rough Surfaces Exhibiting Backscatter Enhancement," with M. El-Shenawee, *Proceedings of the Conference on the Computation of Electromagnetic Fields*, October 1993.

25. "Full Wave Multiple Scatter from One Dimensional Random Rough Surfaces," with M. El-Shenawee, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1316-1319, July 1993.

36

26. "Numerical Solution of Scattering Fields from Rough Surface Using Full Wave Generalized Telegraphists' Equations," with Y. Zhang and S. Shi, *Proceedings of PIERS, Progress in Electromagnetics Research Symposium*, p. 611, July 1993.

27. "Multiple Scattering from One Dimensional Random Rough Surfaces-Full Wave Solutions," with M. El-Shenawee, *Proceedings of PIERS, Progress in Electromagnetics Research Symposium*, p. 610, July 1993.

28. "Radar Cross Sections for Two-Dimensional Random Rough Surfaces with Different Roughness Scales," with B.S. Lee, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1680-1683, June 1994.

29. "Examination of Large Radius of Curvature Approximation for Rough Surface Scatter Cross Sections," with M. El-Shenawee, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1684-1687, June 1994.

30. "Backscatter Modified Mueller Matrix Elements from Stratified Medium," with R.D. Kubik, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1630-1633, June 1994.

31. "Full Wave Scatter Cross Sections for Two-Dimensional Rough Surfaces Using Joint Conditional Surface Height Characteristic Functions," with B.S. Lee, *Proceedings of the 1994 International Geoscience and Remote Sensing Symposium and International Remote Sensing Meeting*, August 1994.

32. "Multiple Scattering from Random Rough Surfaces Based on a Deterministic Full Wave Model," with M. El-Shenawee, *Proceedings of the 1994 International Geoscience and Remote Sensing Symposium and International Remote Sensing Meeting*, August 1994.

C. Papers Accepted for Publication - in Press

1. "Full Wave Single and Multiple Scattering from Rough Surfaces," with M. El-Shenawee, *Journal of Computational Physics*, in press.

2. "Vertically and Horizontally Polarized Diffuse Multiple Scatter Cross Sections of One Dimensional Random Rough Surfaces That Exhibit Enhanced Backscatter-Full Wave Solutions," with M. El-Shenawee, *Journal of the Optical Society of America*, in press.

3. "Enhanced Backscatter from One Dimensional Random Rough Surfaces-Stationary Phase Approximations to Full Wave Solutions," with M. El-Shenawee, Journal of the Optical Society of America, in press.

4. "Numerical Method to Compute TE and TM Multiple Scatter from Rough Surfaces Exhibiting Backscatter Enhanced," with M. El-Shenawee *Proceedings of the Conference on Computation of Electromagnetic Fields*, in press.

5. "Full Wave Scatter Cross Sections for Two-Dimensional Rough Surfaces Using Joint Conditional Surface Height Characteristic Functions," with B.S. Lee, *Proceedings of the 1994 International Geoscience and Remote Sensing Symposium and International Remote Sensing Meeting.* August 1994.

6. "Multiple Scattering from Random Rough Surfaces Based on a Deterministic Full Wave Model," with M. El-Shenawee, *Proceedings of the 1994 International Geoscience and Remote Sensing Symposium and International Remote Sensing Meeting,* August 1994.

7. "Electromagnetic Scattering and Depolarization Across Rough Surfaces – Full Wave Solutions," with G. Huang and B.S. Lee, *Radio Science*, in press.

8. "Full Wave Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces," with B. S. Lee, *IEEE Transactions on Antennas and Propagation*, in press.

9. "Like and Cross Polarized Transmission Scattering Cross Sections for Random Rough Surfaces - Full Wave Solution," with B.S. Lee, G. Huang, and R.D. Kubik, *Radio Science*, in press.

D.   Papers Submitted to Journal Editors for Review

1. "Numerical Solutions for the Scattered Fields from Rough Surfaces Using the Full Wave Generalized Telegraphists' Equations," with Y. Zhang, submitted for review.

IX. ACKNOWLEDGMENTS

X. CONCLUDING REMARKS

The research group at the University of Nebraska-Lincoln has over the three year duration of the ARO Grant, satisfied all the proposed research objectives (including comparisons with theoretical, numerical and experimental results). The problems of multiple (double) scatter and enhanced backscatter has been analyzed and the radar cross sections have been evaluated in a tractable manner. The effects of the rough surface statical parameters on the angular width and level of the enhanced backscatter peak has been considered in detail.

Several new objectives need to be considered for future work in this field. The extension of this work on double scatter from two dimensionally rough surfaces need to be continued (outline of this work is given in Section V). The analytical solutions explicitly relate the rough surface parameters (mean square slope and height, and mean width of typical depressions on the surface) to the quasi parallel and anti-parallel contribution to the double scatter cross sections. It is also necessary to

exploit recent advances in polarimetric radar techniques by measuring all sixteen Mueller matrix elements.

Applications to irregular stratified media should be considered. This work would also be applied to Ellipsometry (quasi specular reflection). Instead of employing effective media parameters to model the effects of rough surfaces on the ellipsometric parameters, a more realistic physical model of the rough surface effects could be developed using the full wave analysis. Thus both the coherent and incoherent components of the Scattering Cross Sections should be evaluated.

A major effort can now be made at the University of Nebraska to compare analytical/numerical results with both in situ measurements as well as controlled laboratory experiments using a 4π Optical Scatterometer (Reflection and Transmission) and Atomic Force/Scanning Tunneling Microscopes. The principal investigator will be submitting proposals to ARO to support the proposed extensions to our investigations.

XI. SEMI ANNUAL/ANNUAL PROGRESS REPORTS

PROGRESS REPORT #1

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 28219-GS

2. PERIOD COVERED BY REPORT: 1 July 1991 – 31 December 1991

3. TITLE OF PROPOSAL: A Full Wave Study of Radar Cross
Sections of Rough Terrain & Foliage
Covered Terrain

4. CONTRACT OR GRANT NUMBER: DAAL03-91-G-0204

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

        See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
DURING THIS REPORTING PERIOD:
    Professor Ezekiel Bahar
    Graduate Research Assistants
      Degrees Awarded (See Attached List)

9. REPORT OF INVENTIONS (BY TITLE ONLY):

E. Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508

1. Papers Presented at Technical Meetings

   (i)   Progress in Electromagnetic Research Symposium, MIT, Cambridge, MA
         July 1-5, 1991, "Two-Dimensional Random Rough Surfaces that Exhibit
         Uniform Enhanced Backscatter for V and H Polarizations Over a Very
         Wide Range of Incident Angles," with R. D. Kubik.

   (ii) Topical Meeting of the International Commission for Optics,
         Atmospheric, Volume and Surface Scattering and Propagation,
         Florence, Italy, August 27-30, 1991, "Single and Multiple Scatter from
         Random Rough Surfaces, Full Wave Solutions," with R. D. Kubik and
         M. El-Shenawee.

   (iii) Advisory Group for Aerospace Research and Development, Fall 1991,
         Electromagnetic Wave Propagation Panel Symposium on Remote Sensing
         of the Propagation Environment, Cesme, Turkey, September 30 - October
         4, 1991, "Active Remote Sensing of the Ionosphere and the Earth
         Surface Irregularities."

2. Papers Accepted for Presentation at Technical Meetings

   (i)   International Union of Radio Science (URSI) Meeting, University
         of Colorado, Boulder, CO, January 7-11, 1992, "Diffuse Incoherent
         Radar Group Cross Sections for Random Rough Surfaces with Height-
         Slope Correlations, Included."

   (ii) Specialist Meeting on Microwave Radiometry and Remote Sensing
         Applications, Boulder, CO, 14-16 January 1992, "Remote Sensing of
         Monomolecular Oil Slicks Characterized by Rough Surface Spectra
         Obtained in Controlled Experiments, Unified Full Wave Approach,"
         with R. D. Kubik.

   (iii) Advisory Group on Aerospace Research and Development (AGARD),
         Electromagnetic Wave Propagation Panel, 50th Symposium on Radio
         Location Techniques, 1-5 June 1992, "Irregular Media Effects on
         Radiowave Signals Used in Navigation and Positioning Systems."

   (iv) 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92)
         Houston, TX, May 26-29, 1992, "Unified Full Wave Solution for
         the Scattering Cross Sections of the Rough Sea Surface Coated with
         a Thin Film of Oil," with R. Kubik.

3. Papers Submitted to Journal Editors for Review

   (i)   "Full Wave Solutions for Rough Surface Bistatic Radar Cross Sections -
         Comparison with Small Perturbation and Physical Optics Solutions,"
         with B. S. Lee.

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING
   THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

   (i) "Full Wave Analysis for Rough Surface Diffuse, Incoherent Radar Cross
        Sections with Height-Slope Correlations Included," IEEE Trans. on
        Antennas and Propagation, Vol. 39, No. 9, pp. 1293-2304, Sept. 1991.

  (ii) "Examination of Full Wave Solutions and 'Exact Numerical Results'
        for One-Dimensional Slightly Rough Surfaces," Journal of Geophysical
        Research, Vol. 96, No. C9, pp. 17,123-17,131, Sept. 15, 1991.

 (iii) "Use of Supercomputers to Evaluate Singly and Multiply Scattered
        Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee,
        IEEE Trans. on Magnetics, Vol. 27, No. 5, pp. 4287-4290, Sept. 1991.

  (iv) "Scattering Cross Sections of Non-Gaussian Rough Surfaces: Unified
        Full Wave Approach," with Y.F. Li, IEEE Trans. on Antennas and
        Propagation, December 1991.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
   DURING THIS REPORTING PERIOD:

   1. Number of Ph.D. degrees____1____

      (i) Magda Osman El-Shenawee, "Full Wave Multiple Scattering
          and Depolarization of Electromagnetic Fields From
          Rough Surfaces."

   2. Number of M.S.E.E. degrees____1____

      (i) Bom Son Lee, "Radar Cross Sections for Random Rough
          Surfaces Using Full Wave Approach with Height/Slope
          Correlation Included."

Brief Outline of Research Findings

During the reporting period (July 1, 1991 - 31 December 1991),
the principal investigator presented three (3) papers at Scientific/
Technical Meetings (see Item #1) and four (4) papers have been accepted
for presentation at International Conferences during the next few months
(see Item #2). One (1) paper has been submitted to the Journal Editor
for review (Preprint enclosed) (see Item #3). Four (4) papers were
published in journals (see Item #7) and reprints of these publications
have been submitted with the report. The Ph.D. dissertation of Ms. M.
El-Shenawee and the M.S. thesis of B. S. Lee are accepted (see
Item #8).

In the paper, "Full Wave Analysis for Rough Surface Diffuse
Incoherent Radar Cross Sections with Height-Slope Correlations Included"
one dimensionally rough surfaces are characterized by four dimensional
joint probability density functions for the heights and slopes at two
points on the surface at a distance x_d apart. It is shown that the
expression for the full wave incoherent diffuse scatter cross section
reduces to the low frequency small perturbation solution when the
surface heights and slopes are small and to the high frequency physical
optics solution when the major cocntributions to the scattered fields
come from the neighborhoods of the stationary phase (specular) points.

Using the super-computer facility at Cornell University (NSF
sponsored) the full wave approach has also been used to evaluate
singly and multiply scattered electromagnetic fields from rough
surfaces (see Item #7). It is shown that for highly reflective
surfaces, multiply scattered fields can make significant contributions
to enhanced backscatter for near normal incidence if the mean square
slopes are large ($\langle h_x^2 \rangle \approx 1$) and the correlation lengths are small
($l_c / \lambda \approx 1$, λ is the free space wavelength.

The principal investigator has been invited by Dr. W. Flood, the project monitor, to participate in a workshop on enhanced backscatter at the University of Colorado, at Boulder, on January 10, 1992 after the International Radio Science Meeting. At the Meeting researchers will present experimental, numerical and analytical studies of rough surface scattering.

An application has been made to the project monitor for matching funds to upgrade our Scanning Tunnelling Microscope/Atomic Force Microscope (STM/AFM) and our optical polarimetric scatterometer. These upgrades should enhance our ability to scan larger areas of the rough surface with the STM/AFM and to enhance the performance of the scatterometer in the backscatter direction.

PROGRESS REPORT #2

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 28219-GS

2. PERIOD COVERED BY REPORT: 1 January 1992 - 30 June 1992

3. TITLE OF PROPOSAL: A Full Wave Study of Radar Cross
Sections of Rough Terrain & Foliage
Covered Terrain

4. CONTRACT OR GRANT NUMBER: DAAL03-91-G-0204

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: _____Ezekiel Bahar_____

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

    See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
DURING THIS REPORTING PERIOD:
    Professor Ezekiel Bahar
    Graduate Research Assistants

9. REPORT OF INVENTIONS (BY TITLE ONLY):

E. Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508

1. Papers Presented at Technical Meetings

 (i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 7-11, 1992, "Diffuse Incoherent Radar Group Cross Sections for Random Rough Surfaces with Height-Slope Correlations, Included."

(ii) Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, Boulder, CO, January 14-16, 1992, "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments, Unified Full Wave Approach," with R. D. Kubik.

(iii) 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting, Houston, TX, May 26-29, 1992, "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film," with R. D. Kubik.

(iv) Advisory Group on Aerospace Research and Development (AGARD), Electromagnetic Wave Propagation Panel, 50th Symposium on Radio Location Techniques, June 1-5, 1992, "Irregular Media Effects on Radiowave Signals Used in Navigation and Positioning Systems."

 (v) 1992 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 22-25, 1992, "Use of a New Polarimetric Optical Bistatic Scatterometer to Measure the Transmission and Reflection Mueller Matrix for Arbitrary Incident and Scatter Direction."

2. Papers Accepted for Presentation at Technical Meetings

 (i) 1992 IEEE-APS International Symposium and URSI Radio Science Meeting, July 20-24, 1992, Chicago, IL, "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee.

(ii) URSI International Symposium on Electromagnetic Theory, Sydney, Australia, August 17-20, 1992, "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics."

3. Papers Submitted to Journal Editors for Review

 (i) "Unified Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland.

(ii) "Full Wave Single and Multiple Scattering from Rough Surfaces," with M. El-Shenawee.

(iii) "Use of a New Polarimetric Optical Bistatic Scatterometer to Measure the Transmission and Reflection Mueller Matrix for Arbitrary Incident and Scatter Directions," with R. D. Kubik and D. R. Alexander.

4. Papers Accepted for Publication

 (i) "Simulation of High Resolution Radar Polarimetric Images - Unified Full Wave Approach," with R. Kubik, International Journal of Remote Sensing.

 (ii) "Identification of Contaminant Coatings Over Rough Surfaces Using Polarized IR Scattering," with S. M. Haugland and A. H. Carrieri, Applied Optics.

(iii) "Active Remote Sensing of the Ionosphere and the Earth Surface Irregularities," Proceedings of the 49th AGARD-EPP Symposium on Remote Sensing of the Propagation Environment, Cesme, Turkey, 1991.

 (iv) "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments: Unified Full Wave Approach," with R. D. Kubik, Proceedings of the Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, July 1992.

(v)   "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee,   Proceedings of the 1992 Antennas and Propagation Society International Symposium, July 1992.

(vi) "Irregular Media Effects on Radiowave Signals Used in Navigation and Positioning Signals," Proceedings of the Advisory Group on Aerospace Research and Development (AGARD) Electromagnetic Wave Propagation Panel, 50th Symposium on Radio Location Techniques, July 1992.

(vii) "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics," Proceedings of the 1992 International Union of Radio Science (URSI) Symposium on Electromagnetic Theory, Sydney, Australia, August 1992.

5. Papers Published

(i) "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film of Oil," with R. D. Kubik, Proceedings of the 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting, June 1992.

6. Participation in Workshop

Workshop on Enhanced Backscatter organized by W. Flood, Army Research Office (P.O. Box 12211, Research Triangle Park, NC) at Boulder, CO, January 10-11, 1992.

BRIEF OUTLINE OF RESEARCH FINDINGS

During this reporting period (January 1, 1992 - June 30, 1992) the Principal Investigator participated in five (5) Scientific/Technical Meetings where five papers were presented (See Item #1), and two (2) papers have been accepted for presentation at International Conferences during the next few months (See Item #2). Three (3) papers were submitted to Journal Editors for review (See Item #3). Seven (7) papers were accepted for publication in Technical/Scientific Journals and Conference Proceedings (See Item #4). One (1) paper was published (See Item #5, Reprints attached). The Principal Investigator participated in the Workshop on Enhanced Backscatter in Boulder, Colorado January 10-11, 1992 organized by Dr. W. Flood of the Army Research Office (See Item #6).

The investigations on the "Full Wave Analysis for Rough Surface Diffuse Incoherent Radar Cross Sections with Height-Slope Correlations Included," (See Semi-Annual Report #1) have been extended to vertically polarized excitations. It is shown that for random rough surfaces with very small Rayleigh roughness parameters $\beta = 4k_o^2 < h^2 >$ (where k_o is the free space wave number and $< h^2 >$ is the man square height) and small slopes ($h_x \approx 0.1$) the full wave solutions for the diffuse scattered vertically polarized waves are in good agreement with the small perturbation solution of Rice. As the slope h_x becomes extremely small, the second order small perturbation solution is not valid. The full wave solution is also compared with the physical optics solution. The scattered vertically polarized full wave radiation fields vanish at grazing angles in agreement with experimental data. The corresponding small perturbation and physical optics solutions do not vanish at grazing angles. This work will be submitted to a technical/scientific journal for publication during the next reporting period.

Progress has also been made on obtaining solutions for multiple scattering from rough surfaces. The work based on a model consisting of random distributions of surface scattering will be presented in July 1992 (See Item #2, (i)) at the IEEE-APS International Symposium in Chicago, Illinois.

PROGRESS REPORT #3

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 28219-GS

2. PERIOD COVERED BY REPORT: 1 July 1992 – 31 December 1992

3. TITLE OF PROPOSAL: A Full Wave Study of Radar Cross Sections of Rough Terrain & Foliage Covered Terrain

4. CONTRACT OR GRANT NUMBER: DAAL03-91-G-0204

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: _____Ezekiel Bahar_____

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

    See Attached List.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:
    Professor Ezekiel Bahar
    Graduate Research Assistants

9. REPORT OF INVENTIONS (BY TITLE ONLY):

E. Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508

1. Papers Presented at Technical Meetings

(i) 1992 IEEE-APS International Symposium and URSI Radio Science Meeting, July 20-24, 1992, Chicago, IL, "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee.

(ii) URSI International Symposium on Electromagnetic Theory, Sydney, Australia, August 17-20, 1992, "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics."

(iii) 124th Meeting of the Acoustical Society of America, New Orleans, LA, November 31-December 4, 1992, "Full-Wave Modeling of the Transmission of Sound over Theater Seats: Far Field Investigation," with D. J. Cheenne, R. D. Kubik and R. C. Maher.

(iv) First International Conference on Planetary Systems: Formation, Evolution and Detection, California Institute of Technology, Pasadena, CA, December 8-10, "Full Wave Solutions to Interpret Planetary Surface Data," with M. Haugland.

2. Papers Submitted for Presentation at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 5-8, 1993, "Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces--Full Wave, Perturbation and Physical Optics Solutions," with B. S. Lee.

(ii) 24th Annual Lunar and Planetary Science Conference, Houston, TX, March 15-19, 1993, "Interpretation of Lunar and Planetary Electromagnetic Scattering Using the Full Wave Solutions," with M. Haugland.

(iii) Progress in Electromagnetic Research Symposium PERS 1993, California Institute of Technology, Pasadena, CA, July 12-16, 1993, "Multiple Scattering from One Dimensional Random Rough Surfaces--Full Wave Solution," with M. El-Shenawee.

(iv) Progress in Electromagnetic Research Symposium, PERS 1993, California Institute of Technology, Pasadena, CA, July 12-16, 1993, "Numerical Solutions of Scattered Fields from Rough Surfaces Using Full Wave Generalized Telegraphists' Equations," with Y. Zhang.

(v) 1993 IEEE-APS International Symposium and Radio Science Meeting, University of Michigan, Ann Arbor, MI, June 27-July 2, 1993, "Full Wave Multiple Scattering from One Dimensional Random Rough Surfaces and High Frequency Stationary Phase Approximations," with M. El-Shenawee.

(vi) XIVth General Assembly of International Union of Radio Science, Commission F Session on Depolarization Due to Rain, Ice and Surface Scattering, Kyoto, Japan, August 25-September 2, 1993, "Tilt Modulation of Like Polarized and Depolarized Cross Sections Used to Characterize Non-Gaussian Rough Surfaces," with R. D. Kubik and Y. F. Li.

(vii) Combined Optical-Microwave Earth and Atmosphere Sensing, Albuquerque, NM, February 22, 1993, "Measurements from a Polarimetric Optical Bistatic Scatterometer," with R. D. Kubik.

(viii) 25th Meeting of the Acoustic Society of America, Session on New Auditorium Acoustics Measurements--Results and Comparisons, Ottowa, Canada, May 17-21, 1993, "Full Wave Modelling of the Transmission of Sound over Theater Seats: Near Field Investigation," with D. J. Cheenne, R. D. Kubik and R. C. Maher.

(ix) 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, <u>Tokyo, Japan</u>, August 18-21, 1993, "High Frequency Approximations to Multiple Scatter by Rough Surfaces that Exhibit Enhanced Backscatter," with M. El-Shenawee.

(x) 1993 International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, <u>Tokyo, Japan</u>, August 18-21, 1993, "Backscatter Mueller Matrix Elements for Irregular Stratified Media," with R. D. Kubik.

(xi) The Third International Symposium on Antennas and EM Theory, <u>Nanjing, P.R. China</u>, September 6-9, 1993, "Comparison of Two Iterative Solutions with Numerical Solutions for Rough Surface Scattering Using the Generalized Telegraphists' Equations," with Y. Zhang.

3. Papers Submitted to Journal Editors for Review

(i) "Full Wave Solutions for Rough Surface Bistatic Radar Cross Sections -- Comparison with Small Perturbation and Physical Optics Solutions," with B. S. Lee.
(ii) "Electromagnetic Scattering and Depolarization Across Rough Surfaces-- Full Wave Solutions," with G. Huang and B. S. Lee.
(iii) "Full Wave Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces," with B. S. Lee.
(iv) "Full Wave Single and Multiple Scattering from Rough Surfaces," with M. El-Shenawee.
(v) "Use of a New Polarimetric Optical Bistatic Scatterometer to Measure the Transmission and Reflection Mueller Matrix for Arbitrary Incident and Scatter Directions," with R. D. Kubik.

4. Papers Accepted for Publication

(i) "Simulation of High Resolution Radar Polarimetric Images -- Unified Full Wave Approach," with R. D. Kubik, in press.
(ii) "Application of Tilt Modulation of the Scatter Cross Sections to Distinguish Between Different Non-Gaussian Rough Surfaces, Unified Full Wave Approach," with R. D. Kubik and Yang-Feng Li, in press.
(iii) "Unified Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland, in press.

5. Papers Published in Technical/Scientific Journals (reprints enclosed)

(i) "Identification of Contaminant Coatings Over Rough Surfaces Using Polarized IR Scattering," with S. M. Haughland and A. H. Carrieri, <u>Applied Optics,</u> Vol. 31, No. 19, July 1, 1992.
(ii) "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments: Unified Full Wave Approach," with R. D. Kubik, <u>Proceedings of the Specialist Meeting on Microwave Radiometry and Remote Sensing Applications,</u> June 1992.
(iii) "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee, <u>Proceedings of the 1992 Antennas and Propagation Society International Symposium,</u> July 1992.
(iv) "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics," <u>Proceedings of the 1992 International Union of Radio Science (URSI) Symposium on Electromagnetic Theory,</u> Sydney, Australia, August 1992.

6. Pre-prints of Articles on Enhanced Backscatter (Enclosed).

Brief Outline of Research Findings

During the reporting period (1 July 1992 - 31 December 1992) the principal investigator submitted papers at four (4) Scientific/Technical meetings (see Item #1) and ten (10) papers were submitted for presentation at international conferences during 1993 (see Item #2). Five (5) papers were submitted to Journal Editors for review (see Item #3). Three (3) papers were accepted for publication in Technical/Scientific Journals (see Item #4) and four (4) were published in Technical/Scientific Journals and Conference proceedings (see Item #5). Reprints of Item #5 are enclosed. Also enclosed are preprints of Item #2 (iii), (v), (ix). The topic in these three preprints is enhanced backscatter due to multiple scatter from rough surfaces.

Very significant progress has been made in developing and executing the computer codes for the bistatic multiple (double) scatter cross sections for one dimensionally random rough surfaces. Both the vertically and horizontally polarized waves are considered. These full wave results are expressed in terms of six dimensional integrals involving two spatial variables, two slope variables, and two wave vector variables. The major contributions come from the quasi-parallel and quasi anti-parallel paths for the field and its complex conjugate. The contribution from quasi anti-parallel paths which is responsible for the enhanced backscatter is also responsible for the observed undulations in the scattered intensity on either side of the backscatter direction. This is due to the interference of the contributions from two adjacent regions of the rough surface.

A high frequency approximation of the full wave results reduces the six dimensional multiple scatter integral into a two-dimensional integral involving the wave vector variables only. These high frequency approximations provide physical insight to the scattering problem. However, they are practically independent of polarization. The results obtained from the six dimensional integrals show significant polarization dependence of the multiply scattered field even though the single scattered field is practically independent of polarization. The full wave expressions offer an explanation to these results. The three enclosed pre-prints provide additional details regarding this phase of our research.

Progress has also been made on the comparison of the numerical solutions to the Generalized Telegraphists' Equations with two single scatter interactive solutions. The interactive solutions are based on the use of "local" basis functions and basis functions associated with the reference coordinate system.

PROGRESS REPORT # 4

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 28219-GS

2. PERIOD COVERED BY REPORT: 1 January 1993 - 31 December 1993

3. TITLE OF PROPOSAL: A Full Wave Study of Radar Cross Sections of Rough Terrain & Foliage Covered Terrain

4. CONTRACT OR GRANT NUMBER: DAAL03-91-G-0204

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

i "Full Wave Solutions for Rough Surface Bistatic Radar Cross Sections - Comparison with Small Perturbation, Physical Optics Solutions Numerical and Experimental Results," with B. S. Lee, *Radio Science*, in press, 1994.

ii "Full Wave Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces," with B. S. Lee, submitted for review.

iii "Vertically and Horizontially Polarized Diffuse Multiple Scatter Cross Sections of One Dimensional Random Rough Surfaces That Exhibit Enhanced Backscatter-Full Wave Solutions," with M. El-Shenawee, submitted for review.

iv "Enhanced Backscatter from One Dimensional Random Rough Surfaces-Stationary Phase Approximations to Full Wave Solutions," with M. El-Shenawee, submitted for review.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:
    E. Bahar
    Graduate Research Assistant

9. REPORT OF INVENTIONS (BY TITLE ONLY):

E. Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508

BRIEF OUTLINE OF RESEARCH FINDINGS

<u>Specific aims</u>: To determine the single and double scatter cross sections for random rough surfaces.

<u>Results</u>: During the reporting period January 1 - December 31, 1993, the principal investigator submitted four papers for publication in Technical/Scientific journals (see item #7). One has been accepted for publication, two others have been revised and resubmitted and the fourth is still under review.

In the paper on full wave solutions for rough surface bistatic radar cross sections, item #7(i) extensive comparisions have been made between the full wave solutions and the small perturbation, physical/geometric optics solutions as well as published numerical and experimental results for horizontally polarized waves.

In the second paper, item #7(ii) the same extensive comparisons are made for the vertically polarized waves.

In the third paper, item #7(iii), vertically and horizontally polarized diffuse double scatter cross sections have been evaluated for our dimensional random rough surfaces that exhibit enhanced backscatter. These solutions are compared with published experimental results. A comprehensive parametric study is also conducted to determine the dependence of the level and the angular width of the sharp enhanced backscatter upon the rough surface characteristics (mean square height, mean square slope and the mean width of a typical depression). The results for the double scatter cross sections are shown to depend upon the polarization of the electromagnetic waves. This is consistant with the experimental results.

The last paper, item #7(iv) deals with enhanced backscatter from random rough surfaces using high frequency-stationary phase approximations to the full wave solutions. These results are simpler to evaluate and provide useful physical insight to the double scatter problem. However, the angular width of the sharp enhanced backscatter cross section is significantly smaller than corresponding results without the high frequency approximations. Furthermore, the stationary phase approximations are practically independent of polarization.

<u>Plans for coming year</u>: Extend the work on the evaluation of the single and double scatter cross section from one dimenstional random rough surfaces to two dimensional rough surfaces.

<u>Publications</u>:

1. "Full Wave Solutions for Rough Surface Bistatic Radar Cross Sections - Comparison with Small Perturbation, Physical Optics Solutions Numerical and Experimental Results," with B. S. Lee, *Radio Science*, in press, 1994.

2. "Full Wave Vertically Polarized Bistatic Radar Cross Sections for Random Rough Surfaces," with B. S. Lee, submitted for review.

3. "Vertically and Horizontially Polarized Diffuse Multiple Scatter Cross Sections of One Dimensional Random Rough Surfaces That Exhibit Enhanced Backscatter-Full Wave Solutions," with M. El-Shenawee, submitted for review.

4. "Enhanced Backscatter from One Dimensional Random Rough Surfaces-Stationary Phase Approximations to Full Wave Solutions," with M. El-Shenawee, submitted for review.